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Evaluation of a Flow Diversion System for Reducing ^{90}Sr Migration from SWSA 4 to White Oak Creek

L. A. Melroy
D. D. Huff

ENVIRONMENTAL SCIENCES DIVISION
Publication No. 2407

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-9374

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NUCLEAR AND CHEMICAL WASTE PROGRAMS
(Activity No. AR 05 10 05 K; ONL-WN 02)

Date Published: May 1985

Prepared for the
Office of Defense Waste and Byproducts Management

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

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ABSTRACT

MELROY, L. A., and D. D. HUFF. 1984. Evaluation of a flow diversion system for reducing ^{90}Sr migration from SWSA 4 to White Oak Creek. ORNL/TM-9374. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 60 pp.

Discharge from the Solid Waste Storage Area 4 (SWSA 4) watershed was studied to determine the extent to which a flow diversion system has reduced the migration of ^{90}Sr into White Oak Creek. The diversion system was built in 1983 to divert runoff from the SWSA 4 catchment headwaters area (56% of the basin) around buried wastes because an earlier study showed that this would be an effective remedial measure for reducing ^{90}Sr migration. The results presented here indicate that the diversion system has reduced the average flow in the SWSA 4 tributary by 56% and the flux of ^{90}Sr by 44%.

A second phase of the study was to rank SWSA 4 and its surrounding areas as sources of ^{90}Sr input to White Oak Creek. Runoff from SWSA 4 contributes about 67% of the local ^{90}Sr input to White Oak Creek and is therefore the major source of contamination. The remaining 33% could be attributed to either groundwater inflows from adjacent contaminated floodplain areas or computational uncertainty arising mainly from errors in the measurement of flow and ^{90}Sr concentration. Preliminary results suggest that it is groundwater transport of ^{90}Sr from adjacent areas that is responsible for the additional inputs.

INTRODUCTION

In humid environments, control of runoff can be a key factor in managing the migration of solutes at shallow land disposal sites. In many cases, groundwater movement is the dominant mechanism of transport, but in other situations, the control of surface runoff is vital to acceptable site performance. Surface runoff control is of particular importance for burial sites located in the lower regions of a watershed, since the potential exists for upslope runoff to leach and transport solutes from the disposal area. This situation was found to exist at Solid Waste Storage Area 4 (SWSA 4) at the Oak Ridge National Laboratory, Oak Ridge, Tennessee, and was described by Huff et al. (1982). They found that surface water runoff was the major factor causing ^{90}Sr transport from the low-level radioactive waste disposal area, and that much of the runoff was generated in the watershed upgradient of the burial site. During storm events, the total ^{90}Sr transport was an average of 2.8 times greater than that during periods without storms. They estimated that an 80% reduction in ^{90}Sr flux from SWSA 4 could be obtained by diverting the upslope surface and subsurface runoff around the trench areas, but that groundwater movement could still result in some ^{90}Sr migration.

As a result of that study, a surface water diversion system was designed and constructed at SWSA 4 in 1983. The objective of the study presented here was to evaluate the effectiveness of the surface water diversion system and also to evaluate the importance of SWSA 4 as a source of ^{90}Sr input to White Oak Creek, which receives the runoff from several other disposal areas.

SITE HISTORY

Located 100 m west of White Oak Creek, SWSA 4 covers approximately 10.0 ha (24.7 acres), with most of the burial ground situated within the watershed shown in Fig. 1. The watershed occupies 24.6 ha (60.7 acres) and drains through a small tributary along the southern edge of the burial ground to White Oak Creek.

In the spring of 1944, a small impoundment was created along White Oak Creek by an earth-fill dam. The dam failed in the fall, but an "intermediate pond" remained until sometime after 1951 (TVA 1951). The pond acted as a settling basin, collecting radionuclide-contaminated sediments, including ^{90}Sr, ^{137}Cs, and $^{239-240}Pu$. The outline of the contaminated area, which is adjacent to the present SWSA 4, is shown in Fig. 1. The concentration of ^{90}Sr in these sediments has been found to range from 8 to 3000 pCi/g (Duguid 1976). Since this area is now subject to runoff from SWSA 4 and flooding action from White Oak Creek, these sediments may contribute to present-day migration of ^{90}Sr, either through leaching or erosion.

Between 1951 and 1959, SWSA 4 was used as a disposal site for low-level radioactive wastes at the Oak Ridge National Laboratory. The wastes were disposed of in trenches and auger holes to depths up to 5-6 m. Beta- and gamma-emitting wastes were covered with a natural soil cover, and alpha-emitting waste was capped with concrete (Lomenick and Cowser 1961). The burial ground was closed in 1959; subsequently, uncontaminated fill and construction debris were placed on the disposal sites, raising the land surface elevation up to 6 m. Webster (1976)

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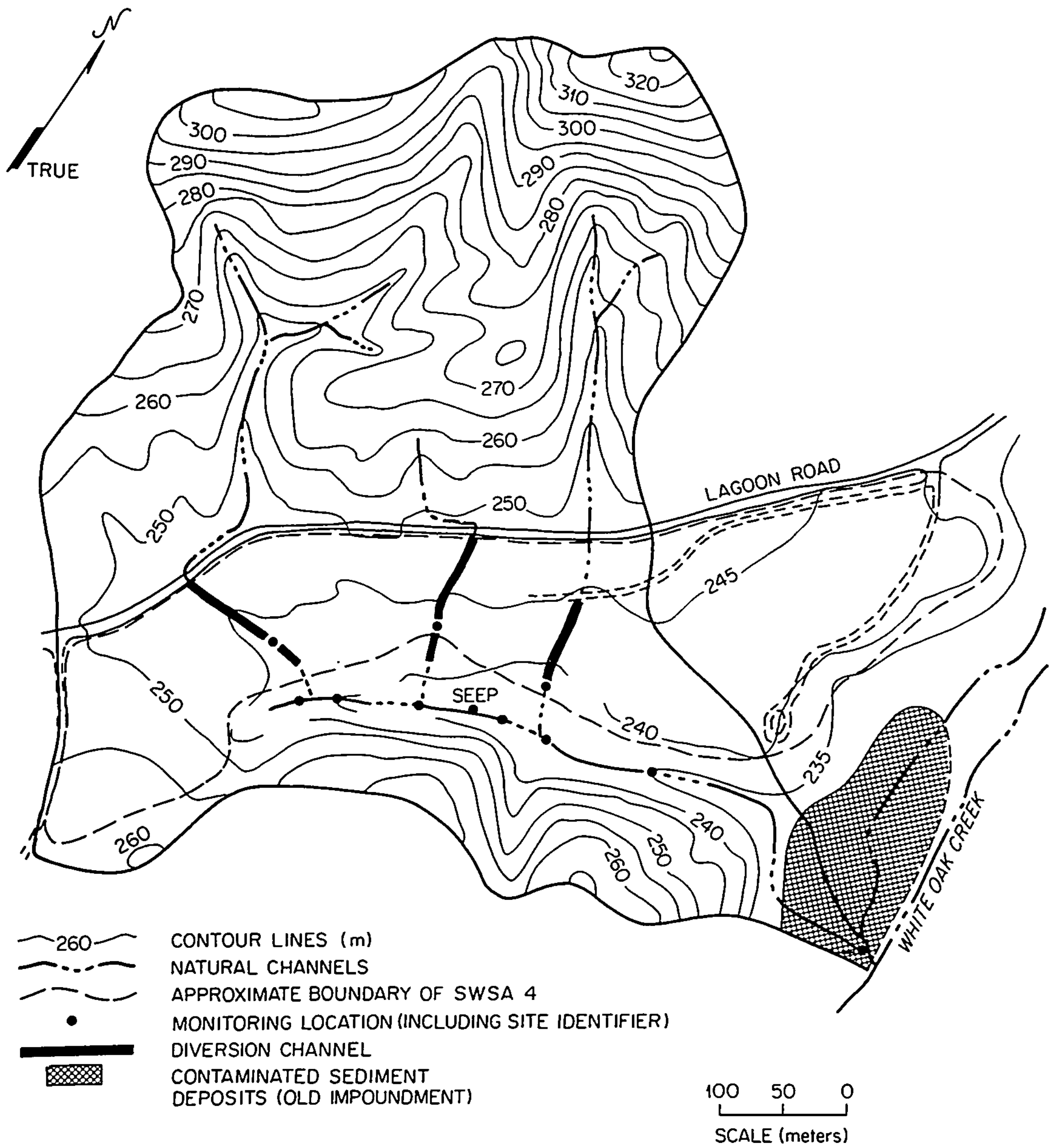

Fig. 1. Map of SWSA 4, showing drainage features before construction of the flow diversion system.

reported evidence that high watertable elevations resulted in some groundwater inundation of trenches during winter periods when the area was not in use. Cowser et al. (1961) also reported that groundwater came in contact with the radioactive wastes, and that contamination could be detected in area wells and seeps at the time disposal operations ceased.

Prior to 1975, the runoff from north of Lagoon Road passed over SWSA 4 through three natural channels, which then entered a small tributary (T-2A) that flows east into White Oak Creek (Fig. 1). In September 1975, recommendations were made to construct a paved interceptor ditch along the northern side of Lagoon Road and to pave the three natural drainage channels. In addition, it was suggested that the burial ground should be capped with a bentonite seal. These actions were suggested in an attempt to reduce infiltration into the burial ground trenches and thus reduce the possibility of groundwater contamination. In 1975, the three drainage channels (shown as diversion channel in Fig. 1) and an interceptor ditch were paved, but the surface seal was not constructed because of budget limitations.

A study conducted by Tamura et al. (1980) to evaluate the impact of the paving of the channels found that no significant reduction in ^{90}Sr migration from SWSA 4 to White Oak Creek had occurred. Steuber et al. (1981) found that SWSA 4 was the major nonpoint source of ^{90}Sr input into White Oak Creek, indicating that further remedial action was necessary. Huff et al. (1982) investigated the sources of ^{90}Sr in runoff from SWSA 4 to determine the hydrologic factors and transport mechanisms affecting ^{90}Sr migration from the burial ground. They found that surface runoff was a major mechanism for ^{90}Sr transport, and estimated that a reduction in the runoff from the upslope watershed area could result in a reduction of up to 80% in the ^{90}Sr flux from the burial ground. They concluded with a recommendation that a surface water diversion system be constructed to divert storm flow.

Based on the study by Huff et al. (1982), a surface water diversion system was designed and constructed at SWSA 4 in September 1983. The primary objective of the diversion project was to capture storm runoff from the catchment north of Lagoon Road (Fig. 2). The major features of the construction were two storm drains, which were buried in trench cuts to allow a continuous downslope gradient from the catch basins to the discharge points. The layout of the diversion project is shown in Fig. 2.

The diversion system consists of a paved interceptor channel, which collects the runoff from north of Lagoon Road, four catch basins (Sites B, C, D, and E shown in Fig. 2), which collect the runoff from the interceptor channel and upslope areas, and the storm drain system, which diverts the runoff around the burial ground.

The area that is affected by the diversion consists of three subwatersheds, which cover 56% of the total watershed area. The easternmost subwatershed occupies 3.6 ha (8.9 acres) and drains to the catch basin at Site B (Fig. 2). The central subwatershed covers only 1.4 ha (3.4 acres), with the runoff entering the storm drain at the catch basin at Site C. The largest subwatershed is the westernmost area, which occupies 8.7 ha (21.6 acres) and drains toward the catch basin at Site D.

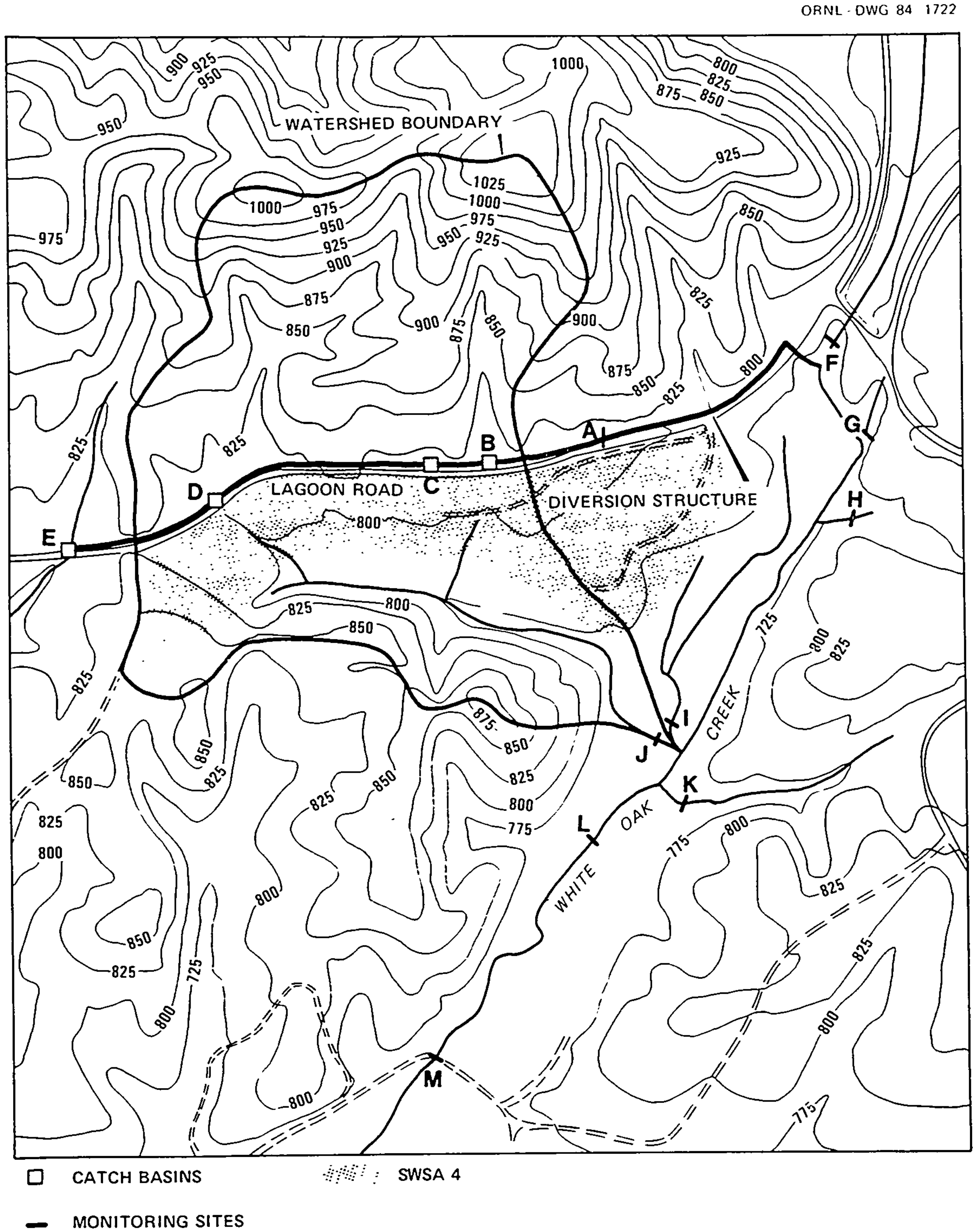

Fig. 2. Map of SWSA 4 site, showing features of the flow diversion system and sampling and flow measurement sites.

The eastern storm drain system consists of an 18-in. (45.72 cm) plastic pipe, connecting Site C to Site B, with a 30-in. (76.2 cm) plastic pipe running from Site B to its discharge point at Site A. At Site A (Fig. 3), the runoff enters a paved channel, where it then flows east to White Oak Creek. The runoff from the catch basin at Site D (Fig. 4) enters a 36-in. (91.44 cm) plastic pipe, which is connected to the catch basin at Site E. Runoff from an adjacent watershed is also collected by the catch basin at Site E, and the combined flow is discharged through a culvert under Lagoon Road to a natural tributary to White Oak Lake.

In addition to the surface runoff collection structures, the storm drain system includes some shallow groundwater collection features. The trench cuts that contain the storm drains have a gravel drain field and perforated piping that parallels the storm drains (between Sites B and A, and Sites D and E), as shown in Fig. 5. This allows interception and diversion of shallow groundwater from part of the area north of Lagoon Road.

EVALUATION OF THE SURFACE WATER DIVERSION PROJECT

METHODS

Evaluation Model

A simple model was used to evaluate the effectiveness of the surface water diversion project. Before construction of the diversion structures, the discharge at Site J consisted of the runoff from the entire watershed, as shown in Fig. 6a:

$$\text{Before diversion:} \quad Q'(\text{Total}) = f(\text{Total area}) \quad . \tag{1}$$

ORNL-PHOTO 7896-83

Fig. 3. Storm drain and diversion channel at Site A, SWSA 4.

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Fig. 4. Catch basin and diversion channel at Site D, SWSA 4.

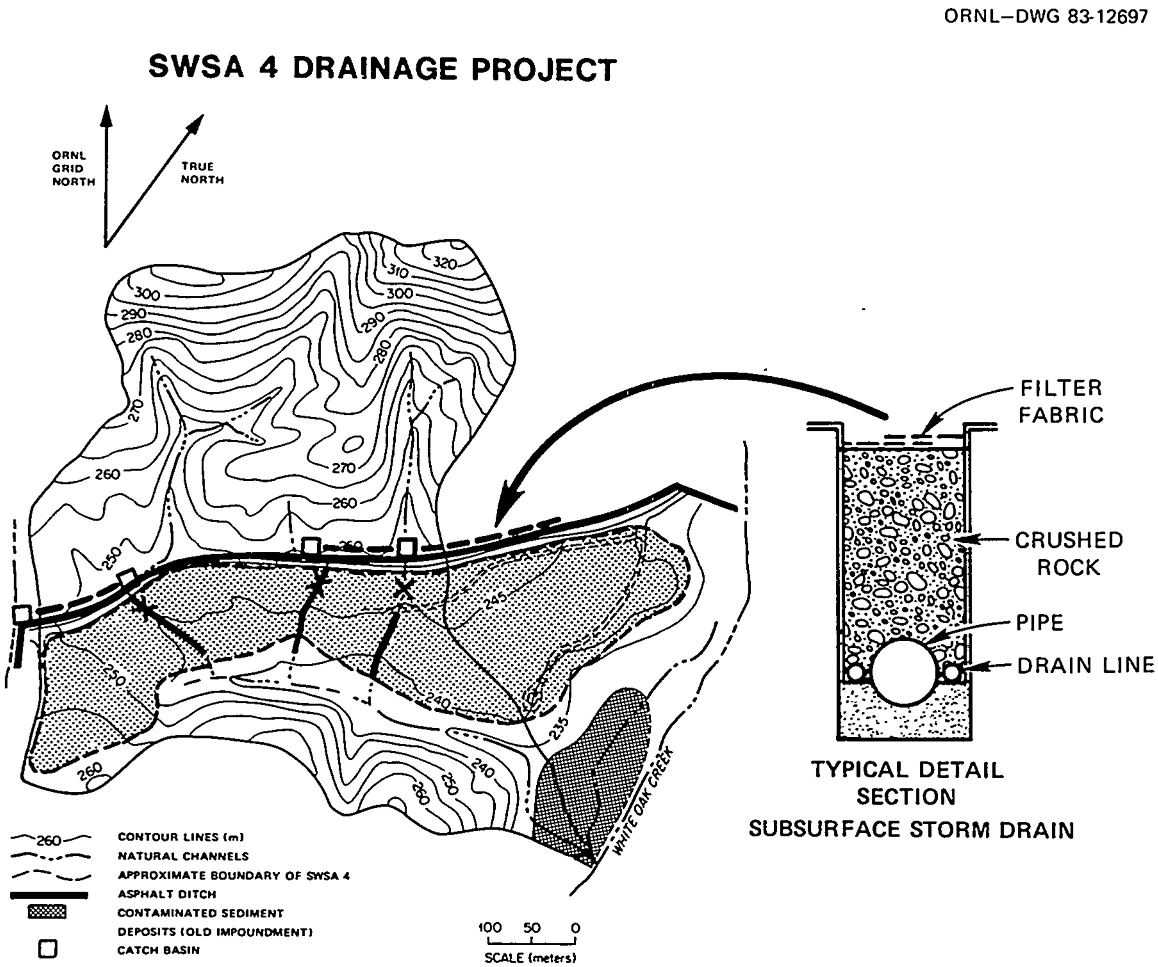

Fig. 5. Map of the SWSA 4 diversion project, showing subsurface drainage features.

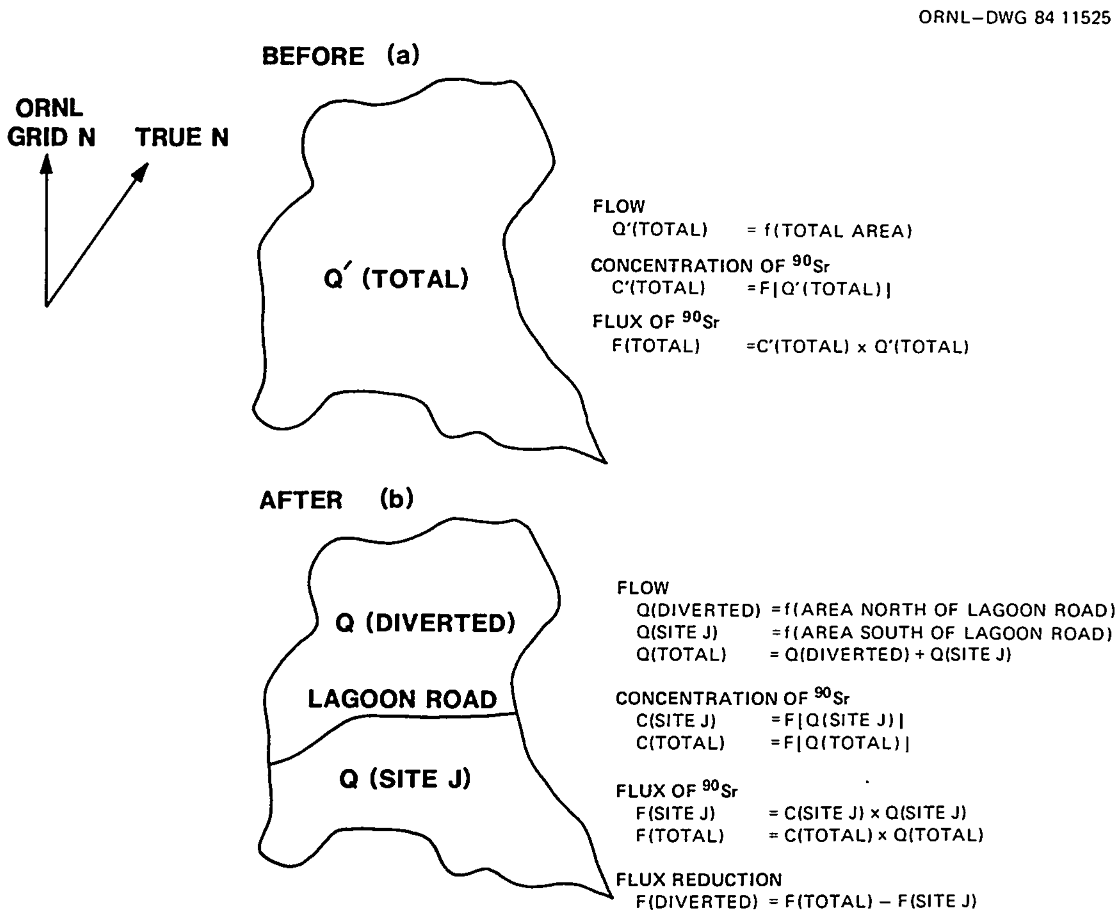

Fig. 6. Model used to evaluate the effects of flow diversion on the flux of ^{90}Sr entering White Oak Creek from SWSA 4.

After the diversion structures were completed, the discharge at Site J was only from the area south of Lagoon Road (Fig. 6b), and the remaining runoff was diverted around the burial ground:

$$\text{After diversion:}\quad Q(\text{Site J}) = f(\text{area south of Lagoon Road}) \quad , \tag{2}$$

$$Q(\text{diverted}) = f(\text{area north of Lagoon Road}) \quad . \tag{3}$$

To estimate the total flow before the diversion, it was assumed that the sum of the discharges from the areas north and south of Lagoon Road was equivalent to the discharge before the diversion construction:

$$\text{Model:}\quad Q(\text{total}) = Q(\text{Site J}) + Q(\text{diverted}) \quad . \tag{4}$$

This model provides a simple method of estimating the quantity of flow that would have occurred at Site J before the diversion system.

The optimum method for determining the volume of flow diverted around SWSA 4 would have been to provide continuous discharge monitoring at the two diversion outfalls. Unfortunately, constraints on the design of the diversion system did not allow installation of hydraulic control structures suitable for continuous monitoring. Therefore, periodic manual measurements of the discharge were made to estimate the average fraction of the total catchment runoff that was diverted. Measurements were taken weekly, with additional measurements taken during storm events. Since the flows could not be measured simultaneously at all locations, the results only approximate the relative distribution of flow. In particular, during intense storm events, the flow may vary quite rapidly, so changes in flow can occur between measurements at the different sites. However, the majority of the measurements were taken during periods of slowly changing flow and, therefore, were not significantly affected by nonsimultaneous measurements.

The next step in modeling the effectiveness of the diversion involves estimating the reduction in ^{90}Sr flux due to the flow changes. In the study by Huff et al. (1982), a correlation was derived relating the concentration of ^{90}Sr to the discharge at Site J. By using this derived relationship (presented in the next section) and the flow measurements, comparisons can be made between the ^{90}Sr concentration before and after the diversion:

$$\text{Before diversion:}\quad C(\text{total}) = f[Q(\text{total})] \quad , \tag{5}$$

$$C(\text{total}) = f[Q(\text{Site J}) + Q(\text{diverted})] \quad . \tag{6}$$

$$\text{After diversion:}\quad C(\text{Site J}) = f[Q(\text{Site J})] \quad . \tag{7}$$

In addition to modeling the changes in the ^{90}Sr concentration in the T-2A tributary, the flux into White Oak Creek may also be analyzed. The flux can be computed from the ^{90}Sr concentration and the flow, as shown in Eqs. (8) and (9):

$$\text{Before diversion:}\quad F(\text{total}) = Q(\text{total}) \bullet C(\text{total}) \bullet 1000 \quad , \tag{8}$$

$$\text{After diversion:}\quad F(\text{Site J}) = Q(\text{Site J}) \bullet C(\text{Site J}) \bullet 1000 \quad , \tag{9}$$

where

Q = discharge in L/s,

C = concentration of ^{90}Sr in pCi/mL,

F = flux of ^{90}Sr in pCi/s.

The reduction in the flux is equal to the difference between the flux before diversion [F(total)] and the flux after diversion [F(Site J)]:

$$\text{Flux reduction:}\quad F(\text{diverted}) = F(\text{total}) - F(\text{Site J}) \quad , \tag{10}$$

$$\text{Flux reduction (\%):}\quad F(\text{reduction}) = [F(\text{diverted})/F(\text{total})] \bullet 100 \ . \tag{11}$$

Correlation Between ^{90}Sr Concentration and Flow

In the study by Huff et al. (1982), a mathematical correlation was determined using 225 data points, relating the discharge rate to the ^{90}Sr concentration at Site J, as shown in Eq. (12):

$$C_p = \{C1 - (C2 \bullet Q) + C3\,[\exp\,(-C4 \bullet Q)]\} \,/\, 2.22 \quad , \tag{12}$$

where

Q = flow at Site J in L/s,

C_p = predicted ^{90}Sr concentration at Site J in pCi/mL,

C1 = 6.3722,

C2 = 0.02132,

C3 = 13.3955,

C4 = 0.06592.

The correlation coefficient for this relationship was 0.87. A plot of this relationship for flows up to 160 L/s is shown in Fig. 7.

Since this relationship was developed in 1980 (before construction of the diversion system), the measured ^{90}Sr concentration data from this study was plotted with the correlation equation in Fig. 7 to check its validity. Also, a comparison between the predicted concentration

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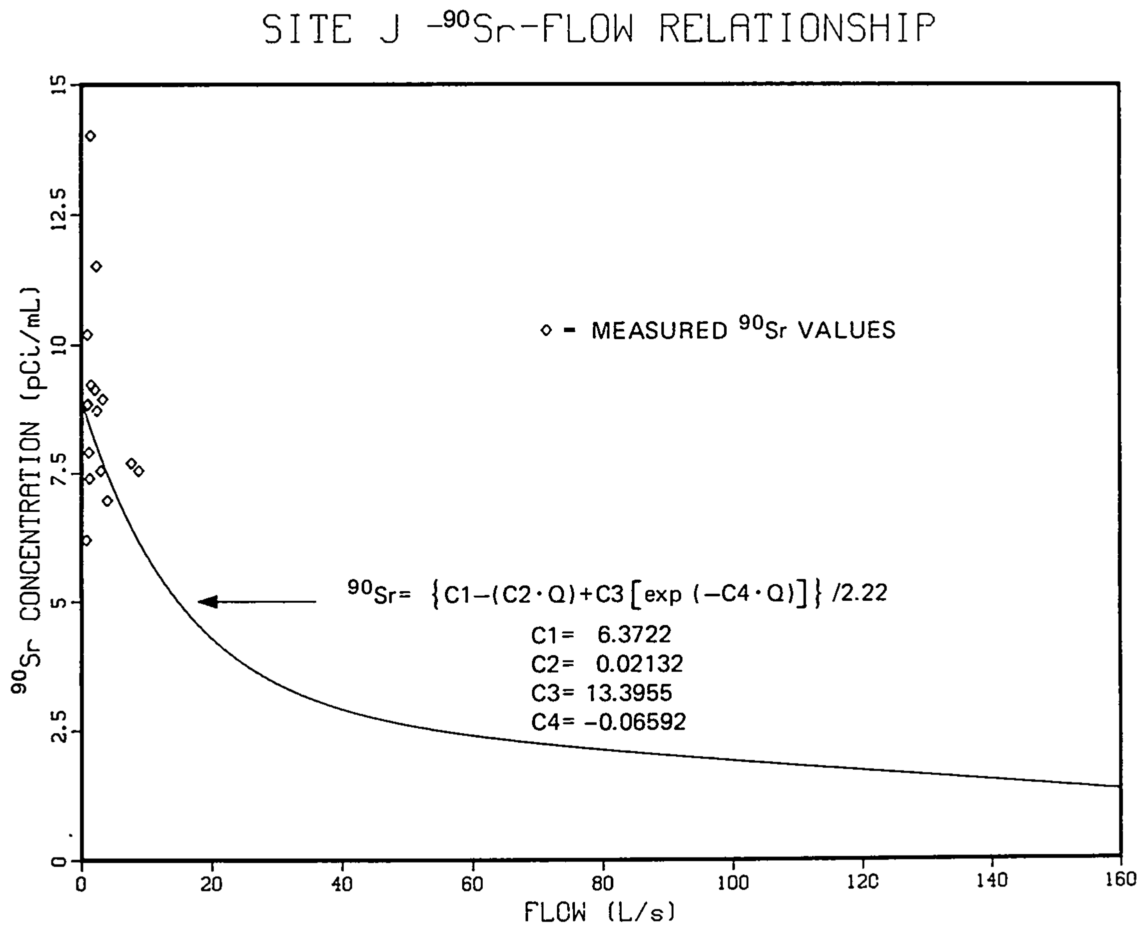

Fig. 7. Relationship between discharge rate and ^{90}Sr concentration at Site J, SWSA 4.

and the observed concentration was made (Table 1). A relative error term was computed, as shown in Eq. (13):

$$\text{Percent error} = [(C_p - C_o)/C_o] \bullet 100 \quad , \tag{13}$$

where

C_o = observed ^{90}Sr concentration at Site J in pCi/mL.

The maximum observed error was -40%, and the average error was -6 ± 18%. Although limited data encompassing relatively low flow conditions were taken to recheck the relationship, there is no evidence to suggest that the relationship has changed since the earlier study. Thus, the original regression equation has been used to predict the ^{90}Sr concentration for the diversion evaluation.

Flow Measurement

The streamflow was measured weekly at Sites A, D, and J (Fig. 2) in order to evaluate the quantity of flow diverted and the total discharge from SWSA 4. At Site A, the flow was measured under a small trough at the outflow from the storm drain by determining the period of time required to fill a bucket of known volume. At Site D, the area-velocity method was used to measure the flow in the channel. Floating chips were used to determine the surface velocity in the channel by timing the period required for the chip to travel a measured distance. Cross-section measurements of the channel were taken so that the stream discharge could be computed.

Table 1. Comparison of measured and predicted concentrations of ^{90}Sr at Site J, SWSA 4

Date	Discharge (L/s)	Measured ^{90}SR concentration (pCi/mL)	Predicted ^{90}SR concentration (pCi/mL)	% Difference in concentration values
01/31/84	1.22	7.40	8.426	13.86
02/15/84	3.94	6.97	7.486	7.40
02/21/84	1.13	7.91	8.460	6.95
03/01/84	2.39	8.717	8.002	-8.20
03/06/84	2.30	11.514	8.033	-30.23
03/12/84	0.96	8.846	8.525	-3.63
03/20/84	1.43	14.02	8.348	-40.46
03/27/84	1.46	9.226	8.337	-9.64
04/03/84	3.27	8.941	7.703	-13.85
04/18/84	0.86	8.83	8.564	-3.01
04/23/84	2.06	9.13	8.118	-11.08
05/01/84	2.94	7.55	7.813	3.48
05/04/84	7.64	7.70	6.444	-16.31
05/09/84	8.78	7.55	6.169	-18.29
05/24/84	0.76	6.20	8.602	38.74
05/31/84	0.92	10.2	8.540	-16.27

At Site J, the streamflow was continuously monitored, using a trapezoidal flume and a portable water-level recorder. To compute the discharge from the flume, the manufacturer provided a rating table and polynomial rating equation, which is presented in Table 2. For comparison, alternative ratings were computed, using the Complex Flume Computer Program (Replogle 1975), which computes the flow based on the flume dimensions and a friction factor. Several ratings were computed, using various friction factors (from 0.009 to 0.00009). The results of these ratings were within 1.5% of one another at the maximum flume depth of 40.45 cm and at a lower depth of 6.20 cm (just above the manufacturer's lower-stage limit), indicating that the computations are insensitive to the friction factor. Table 3 presents a comparison between the discharges for the various friction factors and for the manufacturer's rating. Figure 8 presents curves for the manufacturer's rating (Table 2) and for the complex flume rating for a friction factor of 0.0009 (Table 4), which was chosen because it provided the best correlation with the manufacturer's rating over the largest flow range.

In addition to the continuous flow measurements, bucket measurements were made at Site J, and the measured stage and flow data were plotted with the rating curve (Fig. 8). In the low-flow ranges, a slight shift was observed: for a given stage, the observed discharge was lower than the computed discharge. However, the differences observed were slight and do not affect the results presented in this paper.

A stage recorder was also installed on White Oak Creek below the flume at Site J. During high-flow periods, the backwater created by White Oak Creek flooding can submerge the flume at Site J and result in

Table 2. Manufacturer's rating for the trapezoidal flume at Site J, SWSA 4[a]

Discharge (Q) in cfs, stage (H1) in ft

Q = 2.32 " $H1^{2.5}$ + 0.63 " $H1^{1.5}$ + 0.05

for $0.20 \leq H1 \leq 1.29$

Stage	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.20	0.16	0.18	0.19	0.20	0.22	0.23	0.24	0.26	0.29	0.30
0.30	0.31	0.33	0.35	0.37	0.39	0.42	0.44	0.46	0.48	0.51
0.40	0.54	0.56	0.59	0.62	0.65	0.68	0.71	0.74	0.78	0.81
0.50	0.84	0.88	0.92	0.95	0.99	1.03	1.07	1.11	1.16	1.20
0.60	1.24	1.29	1.34	1.38	1.43	1.48	1.53	1.58	1.64	1.69
0.70	1.74	1.80	1.86	1.92	1.97	2.03	2.10	2.16	2.22	2.29
0.80	2.35	2.42	2.49	2.56	2.63	2.70	2.77	2.84	2.92	3.00
0.90	3.07	3.15	3.23	3.31	3.39	3.48	3.56	3.65	3.74	3.82
1.00	3.91	4.00	4.10	4.19	4.28	4.38	4.48	4.58	4.68	4.78
1.10	4.88	4.98	5.09	5.20	5.30	5.41	5.52	5.63	5.75	5.86
1.20	5.98	6.10	6.21	6.33	6.46	6.58	6.70	6.83	6.96	7.08

[a]Conversion factors: 1 cfs = 28.32 L/s
1 ft = 30.48 cm

Table 3. Comparison of maximum discharges computed for various friction factors and for the manufacturer's rating for the trapezoidal flume at Site J, with a maximum depth of 40.45 cm

Type of theoretical flume rating[a]	Computed discharge (L/s)
Complex flume with f = 0.009	211.01
Complex flume with f = 0.0009	212.77
Complex flume with f = 0.00009	214.28
Manufacturer's rating	214.28

[a] f = friction factor.

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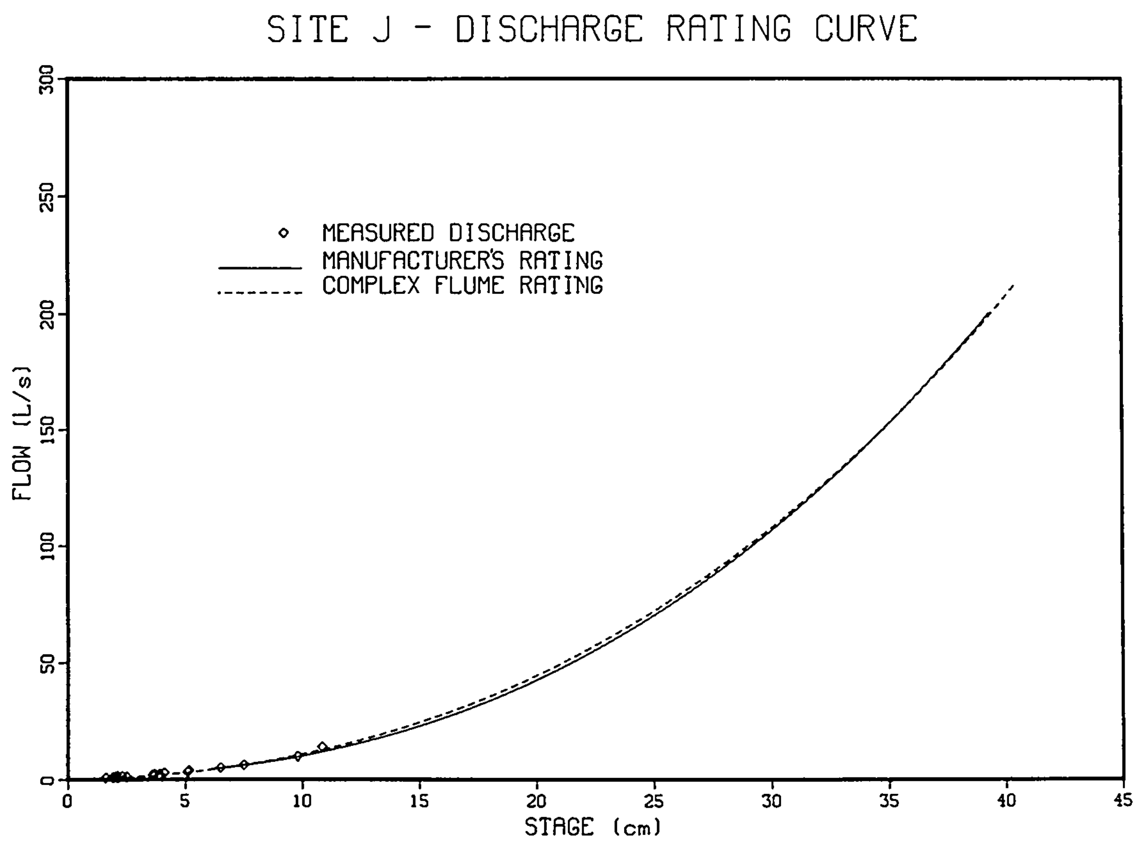

Fig. 8. Discharge rating curves for the trapezoidal flume at Site J, SWSA 4.

Table 4. Computed stage-discharge rating for the trapezoidal flume at Site J, SWSA 4, with a friction factor of 0.0009

Discharge in L/s, maximum depth is 40.45 cm

Depth (D) is expressed as a percentage of the maximum depth.

D	0	1	2	3	4	5	6	7	8	9
0	0.00	0.55	1.22	1.98	2.78	3.64	4.52	5.46	6.44	7.46
10	8.49	9.59	10.70	11.88	13.05	14.29	15.59	16.87	18.21	19.52
20	20.88	22.29	23.76	25.28	26.75	28.26	29.82	31.43	32.99	34.69
30	36.33	38.03	39.76	41.55	43.32	45.19	46.95	48.76	50.74	52.64
40	54.56	56.52	58.53	60.60	62.49	64.65	66.63	68.84	70.90	73.03
50	75.35	77.53	79.77	82.03	84.33	86.45	88.83	91.23	93.44	95.93
60	98.45	100.78	103.16	105.79	108.22	110.69	113.43	115.98	118.56	121.16
70	123.80	126.46	129.18	131.64	134.42	137.22	140.08	142.68	145.57	148.55
80	151.24	154.24	156.98	160.07	162.90	165.73	168.93	171.82	174.77	177.74
90	181.05	184.08	187.17	190.26	193.37	196.51	199.71	202.94	206.17	209.45
100	212.77									

erroneously high stage readings. The stage height recorder was installed to monitor these conditions and allow for adjustment of records during periods of submergence.

RESULTS

Flow determinations were made periodically from February through May 1984 to evaluate the effects of the diversion structures. The flow measurements for Sites A, D, and J are provided in Table 5. At Site A, the observed flows ranged from 0.14 to 70.16 L/s, and at Site D, from 0.095 to 47.47 L/s. From the discharge measurements made at Site J, a high flow of 35.85 L/s and a low flow of 0.76 L/s were observed.

The modeled total discharge before diversion, Q(total), and the diverted discharge, Q(diverted), were computed for these measurements, and the results are shown in Table 5. The flow reduction, in percent, was also computed:

$$\text{Flow reduction (\%)} = [Q(\text{diverted})/Q(\text{total})] \bullet 100 \quad . \qquad (14)$$

The observed flow reductions ranged from 24 to 88%, with an average of 56%. A plot of the flow reduction, in percent, compared to the flow at Site J is shown in Fig. 9. The data show a wide range of scatter, indicating no apparent correlation between the flow at Site J and the degree of flow reduction achieved. Varying external factors, such as precipitation intensity, infiltration rate, and antecedent moisture conditions, will affect how each area of the watershed responds to the rainfall event, so the flow reduction achieved may show some variation between similar precipitation events.

Table 5. Estimated percent flow reduction resulting from diversion of surface water runoff at SWSA 4

	Flow (L/s)					
Date	Q(Site A)	Q(Site D)	Q(Site J)	Q(total)	Q(diverted)	% Flow reduction
02/27/84	6.74	11.35	14.17	32.26	18.09	56.08
03/01/84	1.25	3.05	2.39	6.69	4.30	64.28
03/06/84	0.63	1.06	2.30	3.99	1.69	42.36
03/12/84	0.33	0.41	0.96	1.70	0.74	43.53
03/20/84	2.10	4.74	1.43	8.27	6.84	82.71
03/21/84	8.15	13.99	10.13	32.27	22.14	68.61
03/27/84	0.52	0.39	1.46	2.37	0.91	38.40
03/28/84	20.49	16.11	16.21	52.81	36.60	69.31
04/03/84	0.82	1.03	3.27	5.12	1.85	36.13
04/18/84	0.25	0.29	0.86	1.40	0.54	38.57
04/23/84	1.74	1.13	2.06	4.93	2.87	58.22
04/27/84	2.39	1.48	6.36	10.23	3.87	37.83
04/30/84	4.02	5.26	5.13	14.41	9.28	64.40
05/01/84	2.11	3.26	2.94	8.31	5.37	64.62
05/02/84	70.16	47.47	35.85	153.48	117.63	76.64
05/04/84	4.99	9.75	7.64	22.38	14.74	65.86
05/07/84	40.00	47.03	11.81	98.84	87.03	88.05
05/09/84	4.91	8.27	8.78	21.96	13.18	60.02
05/24/84	0.14	0.095	0.76	0.995	0.235	23.62
05/31/84	0.18	0.37	0.92	1.47	0.55	37.41

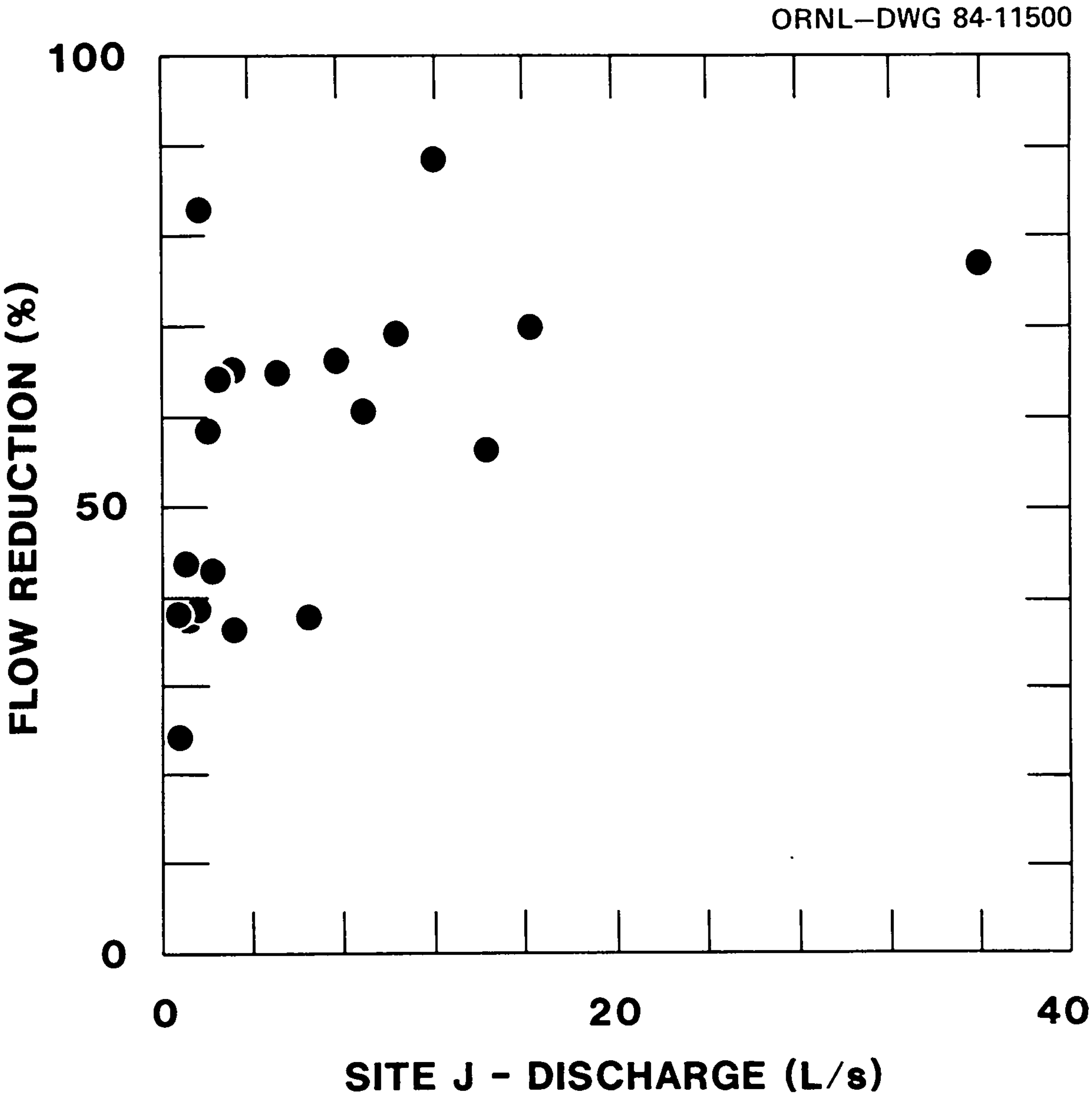

Fig. 9. Plot of the observed flow reduction compared to the measured flow at Site J, SWSA 4.

Using the model previously described (Eqs. 2-12), predictions of the effect of the flow diversion on the ^{90}Sr concentration and flux can be made. The results of these calculations are presented in Table 6.

The estimated ^{90}Sr concentrations at Site J, before flow diversion, ranged from 1.4 to 8.5 pCi/mL. After flow diversion, the estimated levels were between 3.1 and 8.6 pCi/mL. This means that after the flow diversion, because of the inverse exponential relationship between flow and ^{90}Sr concentration, higher concentrations of ^{90}Sr were predicted in the T-2A tributary at Site J, but because of the lower flow volume, the predicted flux rates decreased. At Site J, the flux into White Oak Creek before diversion varied from 8,470 to 214,000 pCi/s. After diversion, the estimated flux ranged from 6,540 to 111,000 pCi/s. The flux reduction predicted was between 1,930 and 125,000 pCi/s, or from 23 to 66%. The average flux reduction was 44%, or 32,700 pCi/s. As a result of the flow diversion system, flow in the T-2A tributary has been reduced, thereby causing higher average ^{90}Sr concentrations due to the inverse relationship between flow and ^{90}Sr concentration (Eq. 12). But, the flux into White Oak Creek was lower due to the lower volume of water.

A plot of the estimated percentage of flux reduction compared to the flow at Site J is shown in Fig. 10. As with the flow reduction plot (Fig. 9), the data do not suggest any strong correlation between the flow and the degree of flux reduction achieved. Therefore, for any given flow rate, the ^{90}Sr reduction achieved is dependent on environmental conditions affecting flow reduction.

Table 6. Evaluation of reduction in ^{90}Sr flux in the SWSA 4 tributary due to diversion of surface water runoff

Date	Concentration (pCi/mL)		Flux (pCi/s)		Flux reduction (pCi/s)	% Flux reduction
	C(total)	C(Site J)	F(total)	F(Site J)		
02/27/84	3.280	5.105	106000	72400	33500	31.63
03/01/84	6.688	8.002	44700	19100	25600	57.26
03/06/84	7.471	8.033	29800	18500	11300	38.01
03/12/84	8.248	8.525	14000	8180	5840	41.63
03/20/84	6.289	8.348	52000	11900	40100	77.05
03/21/84	3.280	5.868	106000	59400	46400	43.84
03/27/84	8.009	8.337	19000	12200	6810	35.88
03/28/84	2.549	4.787	135000	77600	57000	42.35
04/03/84	7.127	7.703	36500	25200	11300	30.97
04/18/84	8.359	8.564	11700	7360	4340	37.07
04/23/84	7.183	8.118	35400	16700	18700	52.77
04/27/84	5.846	6.777	59800	43100	16700	27.93
04/30/84	5.066	7.124	73000	36500	36500	49.94
05/01/84	6.280	7.813	52200	23000	29200	55.98
05/02/84	1.397	3.094	214000	111000	103000	48.26
05/04/84	4.035	6.444	90300	49200	41100	45.49
05/07/84	1.930	5.527	191000	65300	125000	65.78
05/09/84	4.078	6.169	89600	54200	35400	39.53
05/24/84	8.512	8.602	8470	6540	1930	22.81
05/31/84	8.333	8.540	12200	7860	4390	35.86

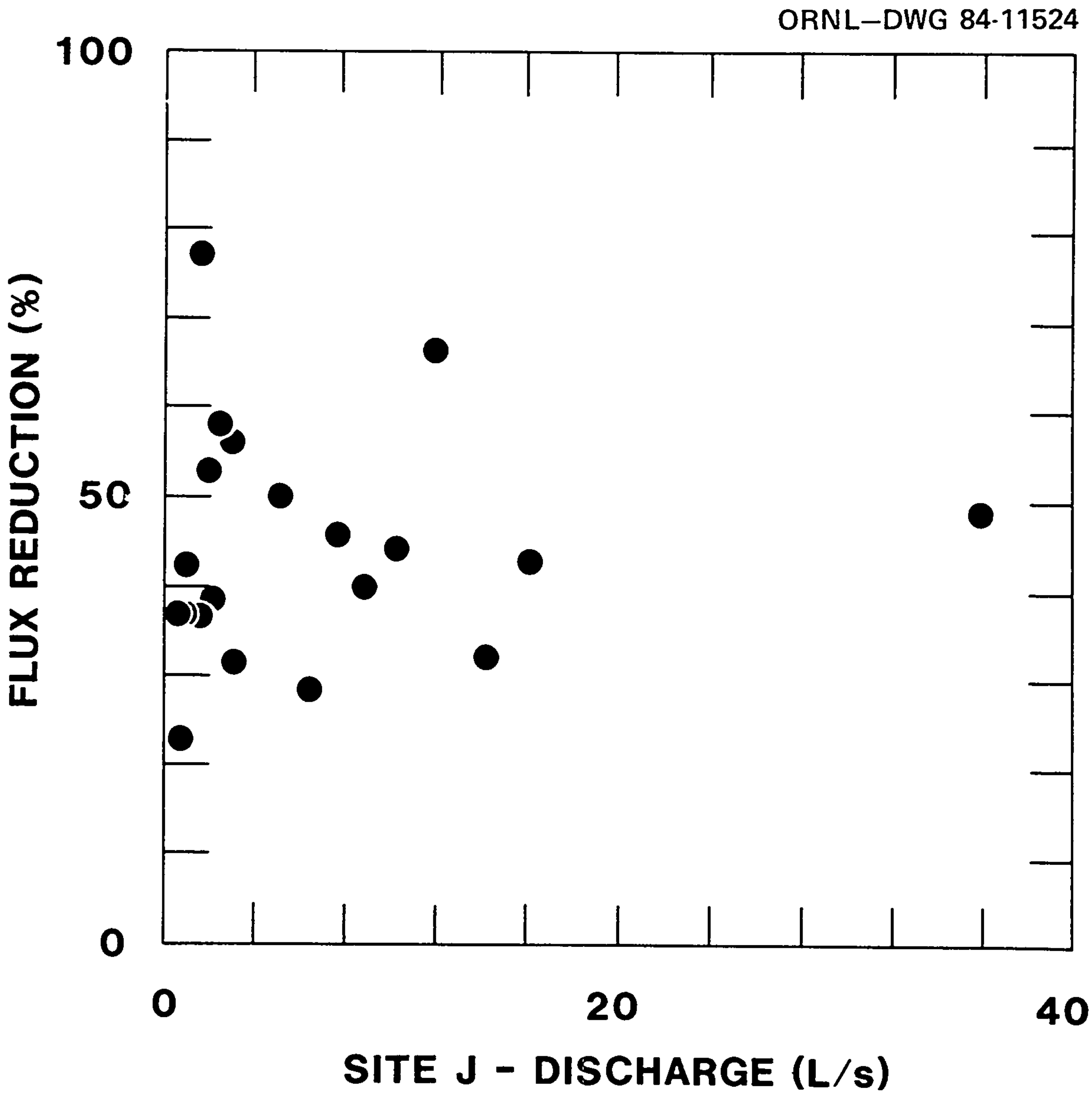

Fig. 10. Plot of the computed flux reduction compared to the measured flow at Site J, SWSA 4.

From the continuous flow monitoring records at Site J and the correlation between ^{90}Sr concentration and flow, estimates of the ^{90}Sr flux from the T-2A tributary were made. In addition, by applying the observed average flow reduction of 56% to these records, estimates of the flow before diversion were also made. Although the flow reduction is not a constant rate, as discussed earlier, the use of an average flow reduction over a long period of time will provide a reasonable approximation of the flow values before diversion. However, since the flow data were taken between February and May, which are generally fairly wet months, the application of these results to dry periods must be undertaken with caution. The continuous flow estimates before diversion were made based on the following relationships:

$$Q(\text{total}) = Q(\text{Site J}) + Q(\text{diverted}) \quad . \tag{4}$$

$$Q(\text{diverted}) = 0.56 \bullet Q(\text{total}) \quad . \tag{15}$$

$$Q(\text{Site J}) = 0.44 \bullet Q(\text{total}) \quad . \tag{16}$$

Therefore, by using the existing flow records at Site J and dividing these values by 0.44, the flow before diversion was estimated. From these records, estimates of the ^{90}Sr flux from the T-2A tributary were made, using the ^{90}Sr concentration-flow correlation. Total flux estimates were made on a monthly basis, using hourly flow values in the computations. The results are provided in Table 7.

During the period of November 1983 through April 1984, the measured flow volume was 40,126 m^3, but before diversion, a volume of 91,195 m^3 was estimated. Therefore, approximately 51,069 m^3 was diverted around SWSA 4. The estimated flux from the T-2A tributary was

Table 7. Monthly ^{90}Sr flux estimates before and after the surface water diversion

Month	Year	After diversion Surface waterflow (M^3)	After diversion ^{90}Sr flux (mCi)	Before diversion Surface waterflow (M^3)	Before diversion ^{90}Sr flux (mCi)
Nov.	1983	3170	20.73	7205	38.50
Dec.	1983	11220	70.03	25500	124.04
Jan.	1984	5794	44.00	13169	85.40
Feb.	1984	5080	34.70	11545	64.66
Mar.	1984	8711	54.30	19798	99.53
Apr.	1984	6150	43.89	13978	84.30
May[a]	1984	5252	36.29	11937	42.85
Total[a]		40126	267.65	91195	496.43

[a]The May 1984 results are not included in the total figures because some of the flow records were lost due to flooding and backwater.

268 mCi, but before diversion, the flux was estimated at 496 mCi, showing a reduction of 228 mCi. This represents an average reduction of 1.26 mCi/day (or 14,500 pCi/s) over the 6-month period, or a total flux reduction of 46%.

From the spot flow measurements, an average flux reduction of 44%, or 32,700 pCi/s, was observed, as mentioned earlier. The reduction achieved in terms of percentage is very consistent between the two estimates. However, when comparing the flux reduction in picocuries per second, the two values differ by 18,200 pCi/s. This difference is due to the fact that the estimates from the field measurements were weighted toward the high-flow, high-flux events, whereas monthly flux estimates include the continuous flow records, which are weighted toward the low-flow, low-flux events. Although a wide range of flow conditions was included in the field measurements, the estimate made from the continuous flow records represents an average of all flow conditions, providing a better estimate of the overall flux reduction.

DISCUSSION

The results of the diversion evaluation have shown that an average flow reduction of 56% and a flux reduction of 44% were attributable to the surface water diversion. Over the 6 months studied, this represents an average flux reduction of 14,500 pCi/s in the T-2A tributary to White Oak Creek.

Of the original SWSA 4 watershed, the runoff from 56% of the area was diverted, and although the average flow reduction was 56%, individual measurements showed significant variation from the average. This observed variation is believed to be due to the nonuniform nature of runoff production over the watershed. For example, the area north of Lagoon Road from which the runoff was diverted is forested, whereas the burial ground is maintained in grass. Also, the northern area is steeper, with a more irregular topography, than the burial ground. Since each of these areas responds differently to a storm event, the runoff response (flow per unit area) will not be the same; thus, the flow reduction will show some variation from one event to the next. But, on the average, both areas of the watershed produced a similiar runoff response, resulting in an average flow reduction equivalent to the watershed area reduction.

In the study by Huff et al. (1982), the off-site runoff, both surface and subsurface, was estimated to account for up to 80% of the ^{90}Sr flux from SWSA 4. However, the diversion structure has not resulted in an 80% flux reduction for several possible reasons: (1) Groundwater was estimated to cause up to 43% of the ^{90}Sr migration during low-flow periods (Huff et al. 1982). Although the diversion structures did include some perforated piping to allow shallow groundwater collection, not all the groundwater was collected, since piping was installed only between Sites A and B, and Sites D and E (Fig. 1). (2) Not all the off-site runoff was diverted. An area of approximately 0.8 ha (2 acres) south of the burial ground still contributes to the runoff of the T-2A tributary, so the flow reduction observed was less than the full potential. (3) Drainage problems associated with the diversion structures may have reduced their effectiveness. These problems are outlined in Table 8, along with possible remedial actions that are currently under consideration.

Table 8. Summary of the remaining drainage problems following construction of the SWSA 4 diversion project

Item	Site	Problem	Corrective action
1	B and D	Construction fill prevents natural channels from draining to the catch basins, which increases infiltration	Removal of construction fill to open natural channels
2	D	Debris clogs grating on the catch basin, which results in overflow to SWSA 4	Routine maintenance especially during and after storm events
3	-	Leakage from the old culverts under Lagoon Road allows flow into SWSA 4	Resealing the old culverts

IMPACT OF SWSA 4 ON WHITE OAK CREEK

OVERVIEW

The White Oak Creek watershed contains several waste disposal areas, so SWSA 4 may not be the only source of contamination to White Oak Creek. Stueber et al. (1981) found that SWSA 4 was the major nonpoint source of ^{90}Sr to White Oak Creek, but since remedial action has been taken there, a reevaluation of the impact of SWSA 4 was desired. Also, since other sources of contamination may exist, such as the sediments from the old impoundment previously mentioned, the location and the impact of these sources are important in assessing the need for further remedial action.

METHODS

Mass Balance Technique

In order to evaluate the relative importance of SWSA 4 as a source of ^{90}Sr input to White Oak Creek, a mass balance was determined for the reach of White Oak Creek adjacent to SWSA 4 and all surface water tributaries between Sites F and M (Fig. 2). Inputs of ^{90}Sr flux to White Oak Creek were computed at four locations (Sites H, I, J, and K), and the net input to White Oak Creek was determined by subtracting the upstream flux from the downstream flux:

$$\text{Net input} = F(\text{Site M}) - F(\text{Site F}) \quad . \tag{17}$$

The measured surface water sources of ^{90}Sr flux were also computed, and the total was determined as follows:

$$\text{Surface influx} = F(\text{Site H}) + F(\text{Site I}) + F(\text{Site J}) + F(\text{Site K}) \quad . \tag{18}$$

The difference between the net ^{90}Sr input to White Oak Creek (between sites M and F) and the measured surface influx represents the contribution from additional nonpoint sources, such as groundwater or overland surface runoff:

$$\text{Additional input} = \text{Net input} - \text{Surface influx} \quad . \tag{19}$$

This additional input term may represent measurement error, groundwater input, or contamination from the floodplain areas. To determine whether this additional input was due to an additional ^{90}Sr source, the net input was compared statistically to the surface influx. If the results indicate that a significant difference exists between the net input and surface influx, then the evidence is strong, but not totally conclusive, that additional ^{90}Sr sources exist. By using a mass balance approach, the various ^{90}Sr sources may be ranked to determine their importance, and any additional contamination sources may be identified.

^{90}Sr Measurement

Water samples were taken for ^{90}Sr analysis on a weekly basis. Grab samples of 500 mL volume were taken at Sites F, H, I, J, K, and L. Additional samples were occasionally taken at Sites A, D, and M. Flow measurements were taken concurrent with the water samples. Note that on White Oak Creek ^{90}Sr samples were taken at Site L, and flow measurements were made at Site M, located further downstream. This was done to avoid the dilution effects from the weir backwater at Site M. The weir forms a rather large pond/backwater, which may result in some undesirable mixing effects. To avoid this problem, the water samples were taken upstream from the weir.

The samples were processed by adding 2 mg of stable strontium carrier in the form of $SrCl_2$ (5.11 g of $SrCl_2$ in 250 mL of H_2O); then they were filtered through Whatman 42 filter paper and acidified with 1 mL of concentrated HCl.

Because of the low concentrations of ^{90}Sr, the samples from Sites A, D, F, H, K, and L were concentrated by evaporating the 500-mL volume to a 20-mL volume. The ^{90}Sr concentration was then determined by Cerenkov counting. When color interference was suspected, samples were spiked with additional ^{90}Sr and recounted to determine counting efficiency. In an earlier study (Huff et al. 1982), the Cerenkov method provided good correlation with the standard radiochemical assay methods for SWSA 4 samples, so the Cerenkov method was used in this study. The results from the ^{90}Sr analyses are shown in Table 9.

Flow Measurement

Flow measurements were taken concurrent with the water samples in order to compute the flux of ^{90}Sr. At Sites F and M, rated weirs were used to determine the flow rate: a trapezoidal weir was used at

Table 9. Measured ^{90}Sr concentration (pCi/mL) at six sites on SWSA 4 and White Oak Creek

Date	Site F	Site H	Site I	Site J	Site K	Site L
01/31/84	0.068	0.02	1.92	7.40	0.06	0.12
02/15/84	0.081	0.003	1.86	6.97	0.056	0.15
02/21/84	0.071	0.006	2.03	7.91	0.05	0.12
03/01/84	0.075	0.0004	1.961	8.717	0.063	0.126
03/06/84	0.131	0.003	2.127	11.514	0.061	0.222
03/12/84	0.119	0.003	2.070	8.846	0.059	0.160
03/20/84	0.089	0.003	2.980	14.02	0.053	0.155
03/27/84	0.096	0.004	2.118	9.226	0.068	0.139
04/03/84	0.085	0.0008	2.32	8.941	0.055	0.192
04/18/84	0.103	0.003	2.08	8.83	0.0618	0.139
04/23/84	0.078	0.001	1.92	9.13	0.068	0.134
05/01/84	0.166	0	1.90	7.55	0.047	0.255
05/04/84	0.191	0[a]	1.74	7.70	0.044	0.296
05/09/84	0.263	0	1.67	7.55	0.058	0.322
05/24/84	0.074	0.003	1.48	6.20	0.055	0.176
05/31/84	0.097	0.003	2.05	10.2	0.048	0.150
06/15/84	0.092	0.002	0	0	0	0.099

[a]Value estimated because lab sample was lost.

Site F, and a dual V-notch weir, at Site M. The rating equations for the weirs are shown below:

$$\text{Site F:}\quad Q = 1131.7(R - 0.0245)^{1.5} \quad , \tag{20}$$

$$\text{Site M:}\quad Q = 202.7(R - 0.484)^{2.4} \quad , \tag{21}$$

where

Q = discharge in L/s,

R = point gage reading in ft.

Both weirs were equipped with brackets designed to hold a point gage to read the water surface elevation.

At the remaining sites, excluding Site L, flow was measured by bucket, except during periods of extremely high flow, when floating chip measurements were made. The results from the flow measurements are presented in Table 10.

RESULTS AND DISCUSSION

From the ^{90}Sr concentration and the streamflow measurements, the ^{90}Sr flux rate (in pCi/s) was computed for the six sites on SWSA 4 and White Oak Creek. The results are provided in Table 11.

The net ^{90}Sr influx was determined by subtracting the upstream from the downstream White Oak Creek fluxes at Sites F and M. These results are shown in Table 12. The surface water ^{90}Sr influx was determined at Sites H, I, J, and K, and the total surface water influx was determined by summation of the influx of those sites (Table 12).

The four surface water sites accounted for an average of 67% of the ^{90}Sr influx to White Oak Creek, with Site J being the major

Table 10. Comparison of the streamflow (L/s) at six sites on SWSA 4 and White Oak Creek

Date	Site F	Site H	Site I	Site J	Site K	Site L
01/31/84	234.84	1.57	1.07	1.22	0.26	271.80
02/15/84	467.29	5.37	2.56	3.94	2.68	541.54
02/21/84	216.00	1.49	1.03	1.13	0.26	245.45
03/01/84	338.78	3.30	1.73	2.39	1.30	400.43
03/06/84	284.69	2.73	1.95	2.30	1.04	329.90
03/12/84	208.23	1.31	0.89	0.96	0.28	240.58
03/20/84	241.91	2.39	1.36	1.43	0.75	298.50
03/27/84	264.58	1.75	1.23	1.46	0.44	307.11
04/03/84	335.38	3.35	1.84	3.27	2.32	482.28
04/18/84	216.00	1.26	0.80	0.86	0.31	257.03
04/23/84	339.92	3.84	2.02	2.06	1.43	400.43
05/01/84	307.49	5.07	2.01	2.94	2.14	371.4
05/04/84	999.46	11.73	6.18	7.64	5.44	1180.89
05/09/84	1152.99	9.25	4.505	8.78	3.19	1308.45
05/24/84	205.34	0.89	0.50	0.76	0.11	249.82
05/31/84	203.42	1.24	0.74	0.92	0.24	232.07
06/15/84	200.55	0.38	0	0	0	222.19

Table 11. Comparison of the ^{90}Sr flux (pCi/s) at SWSA 4 and White Oak Creek

Date	Site F	Site H	Site I	Site J	Site K	Site L
01/31/84	16000	31.4	2050	9030	15.6	32600
02/15/84	37900	16.1	4760	27500	150	81200
02/21/84	15300	8.94	2090	8940	13.0	29500
03/01/84	25400	1.32	3390	20800	81.9	50500
03/06/84	37300	8.19	4150	26500	63.4	73200
03/12/84	24800	3.93	1840	8490	16.5	38500
03/20/84	21500	7.17	4050	20000	39.7	46300
03/27/84	25400	7.00	2600	13500	29.9	42700
04/03/84	28500	2.68	4270	29200	127	92600
04/18/84	22200	3.78	1660	7590	19.2	35700
04/23/84	26500	3.84	3880	18800	97.2	53700
05/01/84	51000	0	3820	22200	100	94700
05/04/84	191000	0	10800	58800	239	350000
05/09/84	303000	0	7520	66300	185	421000
05/24/84	15200	2.67	740	4710	6.05	44000
05/31/84	19700	3.72	1520	9380	11.5	34800
06/15/84	18500	0.76	0	0	0	22000

Table 12. Evaluation of source of ^{90}Sr influx to White Oak Creek

Date	Net ^{90}Sr influx to White Oak Creek (pCi/s)	Measured ^{90}Sr influx in surface water (pCi/s)	Measured ^{90}Sr influx in surface water as percent of the net influx
01/31/84	16600	11100	66.9
02/15/84	43400	32400	74.7
02/21/84	14100	11100	78.3
03/01/84	25000	24300	97.1
03/06/84	35900	30700	85.4
03/12/84	13700	10400	75.5
03/20/84	24700	24100	97.6
03/27/84	17300	16100	93.2
04/03/84	64100	33600	52.5
04/18/84	13500	9280	68.9
04/23/84	27100	22800	84.0
05/01/84	43700	26100	59.8
05/04/84	159000	69800	44.0
05/09/84	118000	74000	62.7
05/24/84	28873	5460	19.0
05/31/84	15000	10900	72.4
06/15/84	3550	0.76	~0.0

source, contributing 56% of the influx. Site I contributed approximately 10% of the ^{90}Sr influx, while Sites H and K contributed less than 1%. Figure 11 shows a bar chart showing the net input of ^{90}Sr to White Oak Creek and the major known inputs.

To test the hypothesis that additional inputs of ^{90}Sr were present along the reach of White Oak Creek adjacent to SWSA 4, a comparison was made between the computed net input and the measured surface influx values. Surface influx measurements accounted for only 67% of the total influx of ^{90}Sr to White Oak Creek. Inherent error in the flow and ^{90}Sr measurements may account for most of this difference. However, a Student's t-test (Appendix) was used on the data, and the results indicated that a significant difference did exist between the net influx to White Oak Creek and the measured surface water influx. This suggests that another ^{90}Sr source is probable. The results are strong, but not conclusive. Possible sources of ^{90}Sr influx to White Oak Creek include input in groundwater from the burial ground and the adjacent contaminated floodplain.

CONCLUSIONS

The evaluation of the surface water diversion system for reducing ^{90}Sr migration from SWSA 4 to White Oak Creek has shown that surface runoff control can be an important factor in controlling ^{90}Sr migration. At SWSA 4, a reduction of the watershed area by 56% resulted in a 44% flux reduction in the T-2A tributary. Also, between November 1983 and May 1984, an estimated 51,069 m^3 of water was diverted by the structure, reducing the flow through the burial ground by 56%.

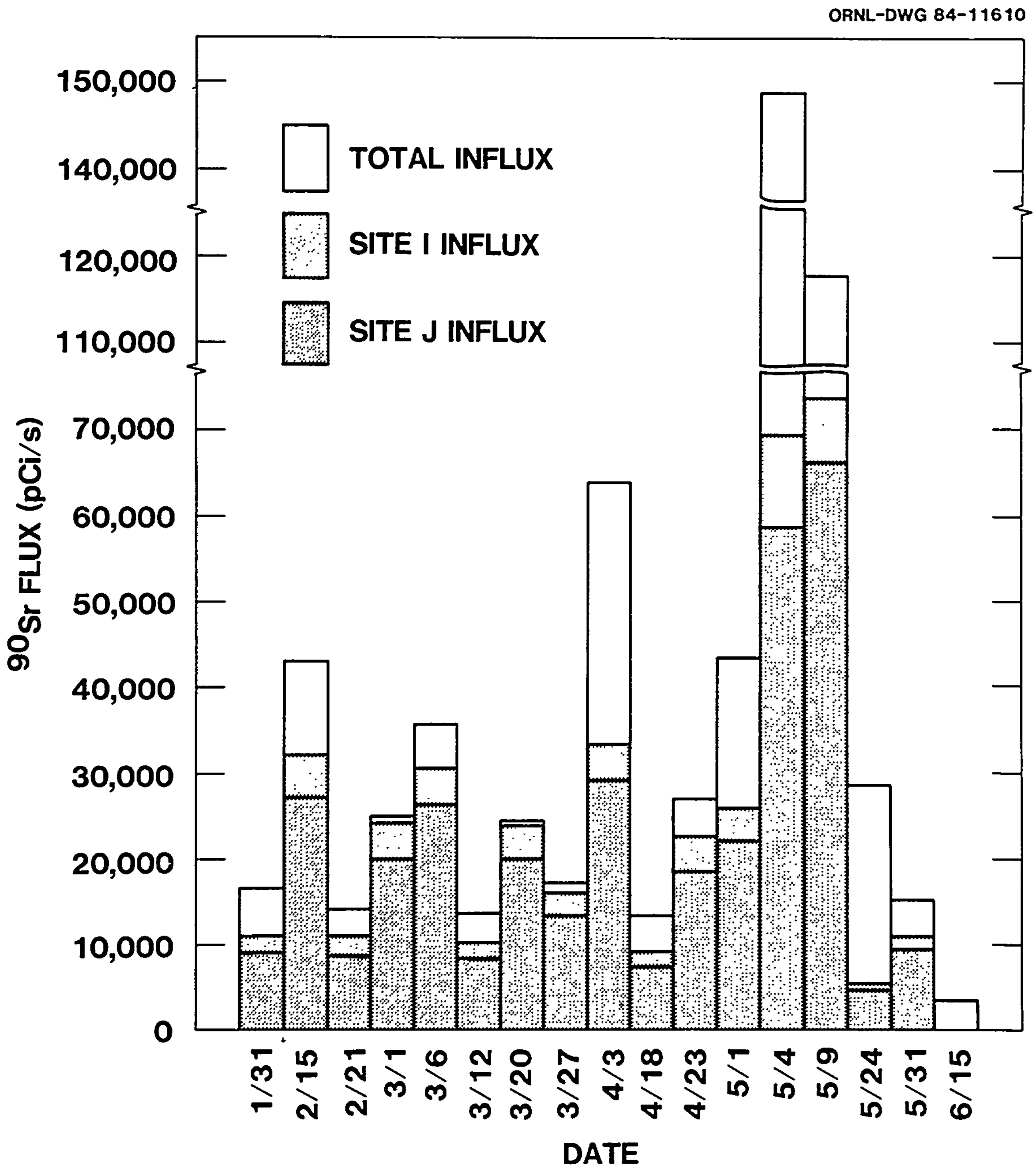

Fig. 11. Measured inputs of ^{90}Sr flux to White Oak Creek in the vicinity of SWSA 4.

Although groundwater is often considered to be the major mechanism of solute transport, surface runoff has been shown to play a significant role in controlling ^{90}Sr migration at SWSA 4.

The diversion structure has substantially reduced the influx of ^{90}Sr into White Oak Creek and represents a significant advance toward site stabilization, even though SWSA 4 remains an important source of contamination to the creek. During the study period, the major source of ^{90}Sr influx to White Oak Creek between Sites F and M (Fig. 2) was SWSA 4 (Site J), but Site I was also a significant source. These two sites accounted for 66% of the present influx to White Oak Creek, with the other three surface water sites accounting for approximately 1% of the influx. The data suggest that the remaining 33% may be due to additional ^{90}Sr sources, such as the contaminated floodplain (Fig. 1), although the evidence is not conclusive.

Although this study did not examine the transport of ^{90}Sr from SWSA 4 in groundwater, the control of groundwater is also an important consideration. Additional work is needed to quantify the groundwater movement and the ^{90}Sr migration in and around SWSA 4 before further remedial action can be recommended. Since several seeps have already been identified at SWSA 4 (Huff et al. 1982), groundwater movement near these seeps should be characterized so that control measures, such as chemical treatment or grouting, can be adequately designed.

Although the contaminated floodplain may also be a source of ^{90}Sr influx to White Oak Creek, quantification of the ^{90}Sr migration in the floodplain is difficult to do with sufficient accuracy because of the large flows in White Oak Creek. Therefore, since other more significant sources of contamination exist, remedial action should be directed first to those sources. To conclude, the remedial action already taken at SWSA 4 has shown that control of surface runoff has reduced ^{90}Sr migration from this shallow land burial site, but further remedial action is required because SWSA 4 still contributes a significant quantity of ^{90}Sr to White Oak Creek.

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APPENDIX

STATISTICAL ANALYSIS OF ^{90}Sr FLUX

A Student's t-test was applied to the flux data to determine if a significant difference exists between the measured and net inputs of ^{90}Sr flux to White Oak Creek. For this statistical test, the difference between the net influx to White Oak Creek and the measured surface water influx (Table 12) was computed. This represents the additional input (Eq. 19) to White Oak Creek. The mean and the standard deviation of the data were determined as shown below:

Additional input (mean) = 14,774.55

s (standard deviation) = 22,596.83

n (number of data) = 17

The Student's t-statistic was then computed from the data:

$$t = \text{additional input (mean)}/(s^2/n)^{0.5} = 2.70 \qquad (22)$$

The Student's t-test was then applied to the results. For a 95% level of significance, with 16 degrees of freedom, the Student's t-statistic was 1.746, for a single-tailed test. Therefore, since the computed t-statistic exceeds the Student's t-statistic distribution, the unknown flux is significantly different from the known surface water influx.

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